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AD 860070

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
ECOM-0381-2

EVALUATION OF ATMOSPHERIC TRANSPORT AND DIFFUSION

SEMI-ANNUAL REPORT

By
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September 1969

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

Contract DAAB07-68-C-0381

DEPARTMENTS OF METEOROLOGY AND OCEANOGRAPHY
TEXAS A&M UNIVERSITY
College Station, Texas

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Reports Control Symbol
OSD - 1366

Technical Report ECOM-0381-2

September 1969

EVALUATION OF

ATMOSPHERIC TRANSPORT AND DIFFUSION

Semi-Annual Report

15 December 1968 to 15 June 1969

Report No. 2

Contract No. DAAB07-68-C-0381

Project 586

Reference 69-11-T

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and Bernice Ackerman

TEXAS A & M RESEARCH FOUNDATION

College Station, Texas

For

U. S. Army Electronics Command, Fort Monmouth, New Jersey

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ABSTRACT

This report summarizes the activities carried out under Signal Corps Contract No. DAAB07-68-C-0381 (Texas A & M Research Foundation Project 586) during the contract period 15 December 1968 through 15 June 1969.

During this period a set of equations which incorporate the momentum and energy sources and sinks due to the trees and foliage were developed for analog simulation of the forest atmosphere. The region above and within the forest are treated separately but are coupled at the top of the canopy.

ACKNOWLEDGEMENT

The research reported herein has been performed under Contract DAAB07-68-C-0381, sponsored by the U. S. Army Electronics Laboratories at Fort Monmouth, New Jersey; however, personnel and equipment support for the General Purpose Analog Computer facility utilized in this research is also provided by the Research Council of Texas A&M University.

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I. Introduction

The trees and attendant foliage of the forest provide a complex distribution of sources and sinks of heat, moisture and momentum. In view of the diverse characters of the atmospheric layers above and interior to the forest, the forested boundary layer is most conveniently considered in two sections: the upper free-air region and the lower forest region.

Experimental systems of equations, with coupling effected through energy and momentum considerations at the top of the forest canopy, have been developed to simulate these two regions. The systems are broadly based on the LLMM with some significant modifications. These sets of equations are now being programmed for analog solution.

The equations used in the simulation are listed in the Appendix and are discussed in Section II. Some of the details of the preliminary simulation plan are given in Section III.

II. Defining Relationships

The equations developed to describe the forested boundary layer are based on the assumptions listed in Semi-Annual Report 1 (hereafter referred to as SR1) plus additional specifications for the free air-canopy interface and the vertical distribution of the exchange coefficient for momentum, K_m. The conditions at the interface are characterized by the conservation of energy at the top of the canopy. The momentum exchange coefficient is assumed constant in the ground layer (depth Δ') and in the air-canopy layer, $(d - \Delta) \leq z \leq (d + \Delta)$, where d is the height of the forest. The values of K_m for these layers are based on Deacon's Beta-equation calculated independently from the vertical gradients of temperature and wind speed just above the forest floor and just above the top of the canopy.

A. Free Air Section

Equations (1) to (18) in the Appendix define the temporal variations of momentum, temperature and vapor pressure in the free air above the forest. These are essentially the same as the atmospheric section of the LLMM with the exception of equations (14) through (16). In view of the current uncertainties in the magnitude of the eddy diffusion coefficients, they are assumed equal in equation (14).

The vertical distribution of the momentum exchange coefficient above the air-canopy layer (Equation (15)) is the same as that in the LLMM except that the entire distribution is lifted a distance equal to the height of the forest, d. The exchange coefficient, K_m, goes to

zero at the top of the boundary layer plus the increment d rather than at Z, the top of the boundary layer itself. Thus the friction layer is deeper than it would be over a smooth surface by an amount equal to the height of the forest. This modification was selected from one of several possibilities because it retained the original vertical distribution yet took into consideration the fact that the roughness was greatly increased. The coefficient b, in Equation (15) is determined in Equation (16) from the requirement that K_m be continuous at the boundary between the air-canopy layer and the free air region.

It is recognized that this approach does not eliminate potential difficulties with poles in the $K_{m(d + \Delta)}$ solution as well as some lack of reality, the latter because the Deacon β equation was developed from data collected in non-forested regimes. However, an alternative is under consideration, if these potential difficulties become real.

B. Free Air-Canopy Section

The relationships for the air-canopy layer are given in Equations (19) through (38) of the Appendix. The most basic equations are (19) and the combination (32), (33) which define respectively, the energy balance and eddy stresses at canopy top.

The energy balance (Equation (19)) recognized that heat may be transferred away from the interface by eddy fluxes of heat and moisture downward through the canopy as well as upward through the free air. The contribution from plant metabolism is much smaller than the other factors and has been neglected.

The net radiation is calculated as in the LLMM except for the modification of the short wave transmissivity of the atmosphere mentioned in SR1. In addition the reflection of long wave radiation by the canopy is neglected, since it represents less than 2 or 3 percent of the up-going long wave radiation.

The eddy fluxes (Equations (25) through (28)) are standard in form. The parameter, ξ, in the equation for the vapor pressure at level d (Equation (29)) is related to the conductivity of the canopy which is a function of a number of variables including leaf area and stomatal resistance. It thus is a problem variable dependent on canopy type and season. Studies currently underway are seeking methods by which this variable may be parameterized.

The stresses at the canopy top are calculated on the implicit assumption of nearly linear change of wind with height through the layer $d - \Delta \leq z \leq d + \Delta$ (Equation (32), (33)). This necessarily puts restrictions on the depth Δ, which will depend on the height and type of forest. The momentum exchange coefficient has been assumed constant through this layer, and is specified by the value at $d + \Delta$, (from Equation (37)) on the assumption that the Deacon profile describes the wind in the layer immediately above the canopy top. The roughness parameter, z_0, for the forest is determined using the empirical relationship developed by Kung (1961). Recent wind tunnel studies of model forests (Hsi and Nath, 1968) indicate that this relationship may be appropriate.

C. The Forest Section

The forest region is naturally the most difficult to formulate not only because of the complex vertical distribution of sources but also because the source terms themselves are complicated and incompletely understood. The momentum sink of the forest is included in the momentum equations (1f) and (2f) by the form drag terms F_x and F_y defined in Equations (9f) and (10f). These are assumed constant throughout the depth of the forest but can be made a function of height if it appears necessary at a later time through the representative coverage factor A. The coverage factor A is a characteristic of the forest and is the effective frontal area per unit depth of forest per unit horizontal area. The drag coefficient, C_D, is the local drag coefficient for the entire forest depth.

The temporal change of temperature, Equation (3f), can be viewed as the sum of a number of contributions: horizontal advection, convective flux divergence, radiation flux divergence, and plant metabolism. The last factor is small relative to the others and can be neglected as it is in the energy balance at the canopy top. The sensible heat (convective) fluxes are calculated in the usual way (Equation (11f), (12f)). There is some difficulty however in determining the proper relationship for R, the radiation flux divergence. This factor must now include the radiation from the trees and foliage as well as the radiation flux from the atmospheric water vapor. There is some evidence, e.g. Denmead, 1964, that the source-sink distributions

of radiant energy are not uniform, so that a simple constancy of radiation flux divergence through the depth of the forest may not be adequate. Studies are currently under way to develop a computational definition of the radiation term based on atmospheric variables.

The moisture expression, Equation (4f) includes the contribution to the moisture content of the air made by evapo-transpiration. A defining expression for this term, M, is being sought in current studies of forest energy budgets. The stress and the convective and evaporative flux equations (7f), (8f), (11f), and (12f), are standard. The eddy diffusion coefficients are assumed equal as they are above the forest (Equation (16f)) but the defining expression for K_m is different. The defining equation for K_m given in Equation (17f) follows from the assumption of a linear distribution between the ground section and the air-canopy layer. The pressure gradient, $\frac{\partial h}{\partial x}$, $\frac{\partial h}{\partial y}$, is considered constant through the depth of the forest and equal to the surface pressure gradient.

The assumption of zero vertical velocity is tentatively maintained pending first testing results and/or more definitive wind data for forested regions. This assumption also holds for the Forest Surface Section discussed below.

D. The Forest Surface Section

The conditions in the forest surface layer, from one meter below the ground surface to a height Δ' above the surface are specified by conservation of energy at the surface and the assumption of constancy of the momentum flux through the layer. The energy budget at the forest surface given in Equation (18f) is the same as that used in

the LLMM. The net radiation considers the down-coming and up-going radiation in both the short wave and long wave parts of the spectrum. The down-coming short wave radiation is expressed as some fraction of that arriving at the top of the canopy, that fraction given by the transmissivity (Equation (20f)). As in the air-canopy section, the reflected long wave radiation is neglected (Equation (23f)). The other expressions for the forest surface layer (Equation (24f) through (37f)) have already been discussed in SR1, except that the depth of the surface layer has been expressed as the variable Δ' rather than as a constant 8m.

III. Layers and Levels

The choice of layers and levels of the forest simulator is somewhat arbitrary for the free-air section. Within the forest, however, these must depend on the depth of the forest. Initially the forested boundary layer will be treated approximately as follows (where d is the height of the forest and Δ' and Δ define the forest surface section and the air-canopy section, resp.)

1. Free Air Section (Equations (1) through (18))

	Levels (m)	Layers (m)
(a)	$z = d + \Delta$	d to $d + 2\Delta$
(b)	$z = d + (32 - \Delta)$	$d + 2\Delta$ to $d + 64$
(c)	$z = d + 107$	$d + 64$ to $d + 150$
(d)	$z = d + 200$	$d + 150$ to $d + 250$

2. Free Air-Canopy Section (Equations (19) through (38))

Levels	Layers
$z = d$	$d - \Delta$ to $d + \Delta$

3. Forest Section

	Levels	Layers
(a)	Δ	surface to $2\Delta'$
(b)	$\frac{d}{2} - (\Delta - \Delta')$	$2\Delta'$ to $d - 2\Delta$
(c)	$d - \Delta$	$d - 2\Delta$ to d

4. Forest Surface Section

Levels	Layers
surface	-1m to Δ'

IV. Experimental Simulation

The equations are being programmed for solution in the analog computer. In this initial simulation the top of the canopy is assumed to be 40m and Δ and Δ' are 5 and 1.5m resp.

The layers and levels there, are as follows.

	Layer	Level	
Free Air	300 - 200m	250m	
	200 - 100	150	
	100 - 50	75	
	50 - 40	45	
- - - - - -	- - - - - - - - - - - -	- - - - - - - - - - - -	40 m
Forest	40 - 30	35	
	30 - 3	15	
	3 - 0	1.5	

One of the primary objectives of the initial simulation will be the test of the energy and momentum source terms proposed for the forest section. In addition, studies will be made to determine how sensitive the model is to other variables and problem parameters.

GLOSSARY

A	characteristic tree coverage	(cm^{-1})
a	ratio of molecular weight of water to molecular weight of dry air	(non-dimensional)
C_D	local drag coefficient	(non-dimensional)
C_p	specific heat of air at constant pressure	(cal/gm deg)
d	height of the effective top of the canopy	(cm)
$D_{\Delta'}$	integral exchange coefficient for momentum between surface and height Δ'	(cm/sec)
e	mean vapor pressure	(mb)
e'	representative vapor pressure	(mb)
$e_{o,s}$	surface saturation vapor pressure	(mb)
$e_{d,s}$	saturation vapor pressure at the temperature of the canopy top	(mb)
F_c	cloud factor for insolation	(non-dimensional)
f	Coriolis parameter	(rad/sec)
F_x, F_y	components of drag force due to trees and foliage	(cm/sec)
G	thermal resistance of surface litter	$(cm^2 sec\ deg/cal)$
g	acceleration due to gravity	(cm/sec^2)
H	hour angle (zero for local apparent noon)	(rad)
h	height of a constant pressure surface	(cm)
I	mean solar constant	$(cal/cm^2 sec)$
i	index	
j	albedo	(non-dimensional)

K_h	exchange coefficient for heat	(cm^2/sec)
K_m	exchange coefficient for momentum	(cm^2/sec)
K_v	exchange coefficient for water vapor	(cm^2/sec)
k	.40 (Von Karman's constant)	(non-dimensional)
L	latent heat of vaporization of water	(cal/gm)
L_N	net longwave radiation	(cal/cm^2sec)
m	empirical radiation factor	(non-dimensional)
n	empirical radiation factor	($mb^{-1/2}$)
M	moisture source term for forest	(mb/sec)
N	turbidity	(non-dimensional)
P	86,400 (diurnal period)	(sec)
p	atmospheric pressure	(mb)
Q	energy addition per unit mass from non-adiabatic processes	(cal/gm)
q	specific humidity	(non-dimensional)
q_c	convective heat flux, positive upward	(cal/cm^2sec)
$q_{c,d+}$	convective heat flux in air layer just above canopy, positive upward	(cal/cm^2sec)
$q_{c,d-}$	convective heat flux in canopy just below the level d, positive downward	(cal/cm^2sec)
q_ε	evaporative heat flux, positive upward	(cal/cm^2sec)
$q_{e,d+}$	evaporative heat flux in air layer just above canopy, positive upward	(cal/cm^2sec)
$q_{e,d-}$	evaporative heat flux in canopy just below the level d, positive downward	(cal/cm^2sec)

q_s	soil heat flux, positive downward	($cal/cm^2 sec$)
R	radiational cooling or warming	(deg/sec)
R_a	gas content for dry air	($cm^2/sec^2 deg$)
R_N	net radiation	($cal/cm^2 sec$)
S	wind speed	(cm/sec)
S_N	net shortwave radiation	($cal/cm^2 sec$)
s_o	surface moistness	($cal/cm^2 sec\ mb$)
T	mean temperature of air	(deg C.)
T'	mean soil temperature	(deg C.)
$\bar{T}_s'$	representative soil temperature	(deg C.)
t	time	(sec)
u	mean east-west component of wind	(cm/sec)
v	mean north-south component of wind	(cm/sec)
u_g, v_g	geostrophic wind components	(cm/sec)
x	east-west coordinate, positive eastward	(cm)
y	north-south coordinate, positive northward	(cm)
Z	105,000	(cm)
z	vertical coordinate, positive upward	(cm)
z_o	surface roughness length	(cm)
zero	as a subscript indicates value at $z = 0$, excepting s_o and z_o	
β	stability parameter in the Deacon profile	(non-dimensional)
δ	solar declination	(rad)
Δ	1/2 depth of air-canopy layer	(cm)

Δ'	depth of forest surface layer	(cm)
Δh	vertical interval between adjacent simulator levels	(cm)
ϵ	emissivity	(non-dimensional)
ζ	solar zenith angle	(rad)
θ	mean potential temperature	(deg C.)
λ	volumetric heat capacity of soil	(cal/cm^{3}deg)
μ	thermal conductivity of soil	(cal/cm sec deg)
ξ	moisture parameter for the canopy	(cal/cm^2 sec mb)
π	3.14. . . .	(non-dimensional)
ρ	air density	(gm/cm^3)
σ	5.67×10^{-5} Stefan-Boltzmann constant	(ergs/cm^{2}sec deg^4)
τ_x	component of τ in x direction	(dynes/cm^2)
τ_y	component of τ in y direction	(dynes/cm^2)
ϕ	latitude	(deg)
χ	forest transmissivity	(non-dimensional)
ψ	solar distance factor	(non-dimensional)
ω	7.3×10^{-5} (angular velocity of earth's rotation)	(rad/sec)

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Hsi, G., and Nath, J. H. (1968). "Wind Drag Within a Simulated Forest Canopy Field." Fluid Dyn. and Diff. Lab., Col. State Univ., Rpt. no. CER68-69GH-JHN6.

Kung, E. (1961). "Derivation of Roughness Parameters from Wind Profile Data Above Tall Vegetation. Studies of the Three Dimensional Structure of the Planetary Boundary Layer," H. Lettau, ed. Univ. of Wisc., Dept. of Meteor. Annual Rpt. under contract DA-36-039-SC-80282. Aug. 1961. pp. 27-37.

APPENDIX

A. Free Air Section

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - g\frac{\partial h}{\partial x} + fv + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z} \quad (1)$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial y} - v\frac{\partial v}{\partial y} - g\frac{\partial h}{\partial y} - fu + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z} \quad (2)$$

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - \frac{1}{\rho C_p}\frac{\partial q_c}{\partial z} + R \quad (3)$$

$$\frac{\partial e}{\partial t} = -u\frac{\partial e}{\partial x} - v\frac{\partial e}{\partial y} - \frac{p}{\rho a L}\frac{\partial q_e}{\partial z} \quad (4)$$

$$p = p_o - \rho g z \quad (5)$$

$$f = 2\omega \sin \phi \quad (6)$$

$$\tau_x = \rho K_m \frac{\partial u}{\partial z} \quad (7)$$

$$\tau_y = \rho K_m \frac{\partial v}{\partial z} \quad (8)$$

$$q_c = -\rho C_p K_h \frac{\partial T}{\partial z} \quad (9)$$

$$q_e = -\rho L K_v \frac{\partial q}{\partial z} \quad (10)$$

$$q = \frac{ae}{p} \quad (11)$$

$$R = \frac{1}{C_p}\frac{dQ}{dt} \quad (12)$$

$$\rho = \left(\frac{p}{R_a T}\right)_{t=0} \quad (13)$$

$$K_m = K_h = K_v \quad (14)$$

$$K_m = b\left(\frac{z-d}{Z}\right)\left(1 - \frac{z-d}{Z}\right)^2 \; ; (d+\Delta) < z < (Z+d) \tag{15}$$

$$b = \left(\frac{Z}{\Delta}\right)\left(\frac{Z}{Z-\Delta}\right)^2 K_{m,d+\Delta} \tag{16}$$

$$\left(\frac{\partial h}{\partial x}\right)_{i+1} = \left(\frac{\partial h}{\partial x}\right)_i + \frac{\Delta h_{n,n+1}}{T}\left(\frac{\partial T}{\partial x}\right)_{i,i+1} \tag{17}$$

$$\left(\frac{\partial h}{\partial y}\right)_{i+1} = \left(\frac{\partial h}{\partial y}\right)_i + \frac{\Delta h_{n,n+1}}{T}\left(\frac{\partial T}{\partial y}\right)_{i,i+1} \tag{18}$$

B. Free Air-Canopy Section

$$R_N = (q_{c,d+} + q_{e,d+}) + (q_{c,d-} + q_{e,d-}) \tag{19}$$

$$R_N = S_N + L_N \tag{20}$$

$$S_N = (1 - j) I \psi \cos \zeta \; e^{-N_{F_c}} \tag{21}$$

$$\cos \zeta = \sin \phi \sin \delta + \cos \phi \cos \delta \cos H \tag{22}$$

$$H = 15(t - 12) \tag{23}$$

$$L_N = \sigma T^4_{d+\Delta} \left(m + n\sqrt{e'_{d+\Delta}}\right) - \varepsilon \sigma T^4_d \tag{24}$$

$$q_{c,d+} = \rho \; C_p \; K_{m,d}(T_d - T_{d+\Delta})/\Delta \tag{25}$$

$$q_{c,d-} = \rho \; C_p \; K_{m,d}(T_d - T_{d-\Delta})/\Delta \tag{26}$$

$$q_{e,d+} = \rho \; a \; L \; K_{m,d}(e_d - e_{d+\Delta})/p_d\Delta \tag{27}$$

$$q_{e,d-} = \rho \; a \; L \; K_{m,d}(e_d - e_{d-\Delta})/p_d\Delta \tag{28}$$

$$e_d = e_{d,s} - \frac{q_{e,d+}}{\xi}; \; q_{e,d+} > 0 \tag{29}$$

$$e_d = e_{d,s}; \; q_{e,d+} \leq 0 \tag{30}$$

$$e_{d,s} = 6.11 \times 10^i; \; i = \frac{7.5 T_d}{237.3 + T_d} \tag{31}$$

$$\tau_{x,d} = \rho \; K_{m,d} \frac{(u_{d+\Delta} - u_{d-\Delta})}{2\Delta} \tag{32}$$

$$\tau_{y,d} = \rho K_{m,d} \frac{(v_{d+\Delta} - v_{d-\Delta})}{2\Delta} \quad (33)$$

$$S_{d+\Delta} = (u_{d+\Delta}{}^2 + v_{d+\Delta}{}^2)^{1/2} \quad (34)$$

$$Ri_{d+\Delta} = \frac{\Delta g(\theta_{d+\Delta} - \theta_d)}{\bar{\theta}(S_{d+\Delta} + 300)^2} \quad (35)$$

$$\beta = 1.003 - 1.163Ri_{d+\Delta} - 9.627Ri_{d+\Delta}{}^2 \quad (36)$$

$$K_{m,d+\Delta} = \frac{(\Delta)^{\beta}(1 - \beta)k^2 z_o{}^{(1-\beta)} S_{d+\Delta}}{[(\frac{\Delta}{z_o})^{(1-\beta)} - 1]} \quad (37)$$

$$\log z_o = -1.24 + 1.19 \log d \quad (38)$$

C. Forest Section

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - g \frac{\partial h}{\partial x} + fv + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} + F_x \quad (1f)$$

$$\frac{\partial v}{\partial t} = -u \frac{\partial v}{\partial y} - v \frac{\partial v}{\partial y} - g \frac{\partial h}{\partial y} - fu + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z} + F_y \quad (2f)$$

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - \frac{1}{\rho C_p} \frac{\partial q_c}{\partial z} + R \quad (3f)$$

$$\frac{\partial e}{\partial t} = -u \frac{\partial e}{\partial x} - v \frac{\partial e}{\partial y} - \frac{p}{\rho a L} \frac{\partial q_e}{\partial z} + M \quad (4f)$$

$$p = p_o - \rho g z \quad (5f)$$

$$f = 2\omega \sin \phi \quad (6f)$$

$$\tau_x = \rho K_m \frac{\partial u}{\partial z} \quad (7f)$$

$$\tau_y = \rho K_m \frac{\partial v}{\partial z} \quad (8f)$$

$$F_x = 1/2\ A\ C_D\ u_g^2 \tag{9f}$$

$$F_y = 1/2\ A\ C_D\ v_g^2 \tag{10f}$$

$$q_c = -\rho C_p K_h \frac{\partial T}{\partial z} \tag{11f}$$

$$q_e = -\rho L K_v \frac{\partial q}{\partial z} \tag{12f}$$

$$q = \frac{ae}{p} \tag{13f}$$

$$R = \frac{1}{C_p} \frac{dQ}{dt} \tag{14f}$$

$$\rho = \left(\frac{p}{R_a T}\right)_{t=0} \tag{15f}$$

$$K_m = K_h = K_v \tag{16f}$$

$$K_m = K_{m,\Delta'} + \frac{K_{m,d-\Delta} - K_{m,\Delta'}}{(d - \Delta) - \Delta'} (z - \Delta') \tag{17f}$$

D. Forest Surface Section

$$q_{c,o} + q_{e,o} + q_{s,o} - R_N = 0 \tag{18f}$$

$$R_N = S_N + L_N \tag{19f}$$

$$S_N = \chi[I\ \psi \cos \zeta\ e^{-N_{F_c}}](1 - j) \tag{20f}$$

$$\cos \zeta = \sin \phi \sin \zeta + \cos \phi \cos \zeta \cos H \tag{21f}$$

$$H = 15(t - 12) \tag{22f}$$

$$L_N = \sigma T_{\Delta'}^4 (m + n\sqrt{e_{\Delta'}}) - \varepsilon \sigma T_o^4 \tag{23f}$$

$$e_o = e_{o,s} - \frac{q_{e,o}}{s_o} \qquad q_{e,o} > 0 \tag{24f}$$

$$e_o = e_{o,s} \qquad q_{e,o} \leq 0 \tag{25f}$$

$$T_o' = T_o - Gq_{s,o} \tag{26f}$$

$$q_{e,o} = \rho aLD_{\Delta'}(e_o - e_{\Delta'})/p_o \tag{27f}$$

$$q_{c,o} = \rho C_p D_{\Delta'}(T_o - T_{\Delta'}) \tag{28f}$$

$$q_{s,o} = \left(\frac{\pi\lambda\mu}{P}\right)^{1/2}(T_o' - T_s') + \left(\frac{P\lambda\mu}{4\pi}\right)^{1/2} \frac{dT_o'}{dt} \tag{29f}$$

$$\tau_{x,o} = \rho D_{\Delta'} u_{\Delta'} \tag{30f}$$

$$\tau_{y,o} = \rho D_{\Delta'} v_{\Delta'} \tag{31f}$$

$$e_{o,s} = 6.11 \times 10^{i} \; ; \quad i = \frac{7.5T_o}{237.3 + T_o} \tag{32f}$$

$$S_{\Delta'} = (u_{\Delta'}^2 + v_{\Delta'}^2)^{1/2} \tag{33f}$$

$$Ri_{\Delta'} = \frac{\Delta' g(\theta_{\Delta'} - \theta_o)}{\bar{\theta}(S_{\Delta'} + 300)^2} \tag{34f}$$

$$\beta = 1.003 - 1.163Ri_{\Delta'} - 9.627Ri_{\Delta'}^2 \tag{35f}$$

$$D_{\Delta'} = \left[\frac{k(1 - \beta)}{\left(\frac{\Delta'}{z_o}\right)^{(1-\beta)} - 1}\right]^2 S_{\Delta'} \tag{36f}$$

$$K_{m,\Delta'} = \frac{(\Delta')^{\beta}(1 - \beta)k^2 z_o^{(1-\beta)} S_{\Delta'}}{\left[\left(\frac{\Delta'}{z_o}\right)^{(1-\beta)} - 1\right]} \tag{37f}$$

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Texas A & M Research Foundation College Station, Texas	2a. REPORT SECURITY CLASSIFICATION
	2b. GROUP

3. REPORT TITLE

Evaluation of Atmospheric Transport and Diffusion

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Second Semi-Annual Report for 15 December 1968 to 15 June 1969

5. AUTHOR(S) (First name, middle initial, last name)

William H. Clayton, Tom E. Sanford, and Bernice Ackerman

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1969	28	3

8a. CONTRACT OR GRANT NO. DAAB07-68-C-0381	9a. ORIGINATOR'S REPORT NUMBER(S) Reference 69-11-T
b. PROJECT NO.	
c. 586	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ECOM-0381-2
d.	

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Electronics Command Fort Monmouth, New Jersey 07703 AMSEL-BL-FM-T

13. ABSTRACT

This report summarizes the activities carried out under Signal Corps Contract No. DAAB07-68-C-0381 (Texas A & M Research Foundation Project 586) during the contract period 15 December 1968 through 15 June 1969.

During this period a set of equations which incorporate the momentum and energy sources and sinks due to the trees and foliage were developed for analog simulation of the forest atmosphere. The region above and within the forest are treated separately but are coupled at the top of the canopy.

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Meteorology						
2. Atmospheric Transport and Diffusion						
3. Department of the Army Contract No. DAAB07-68-C-0381						

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